КВАНТОВЫЕ ГЕЙТЫ И ИХ ФИЗИЧЕСКИЕ РЕАЛИЗАЦИИ

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11.02.22

Что необходимо для квантовых вычислений?

- Необходимо управлять состоянием одного кубита
- Обеспечивать взаимодействие между кубитами

Зачем нужен универсальный набор квантовых гейтов?

Трёхкубитный гейт Дойча:

$$\text{DEUTSCH} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & i\cos(\theta) & \sin(\theta) \\ 0 & 0 & 0 & 0 & 0 & 0 & \sin(\theta) & i\cos(\theta) \end{pmatrix}$$

Results on two-bit gate design for quantum computers

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Универсальный двухкубитный гейт:

$$\text{BARENCO} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & e^{i\alpha}\cos(\theta) & -ie^{i(\alpha-\phi)}\sin(\theta) \\ 0 & 0 & -ie^{i(\alpha+\phi)}\sin(\theta) & e^{i\alpha}\cos(\theta) \end{pmatrix}$$

A Universal Two–Bit Gate for Quantum Computation

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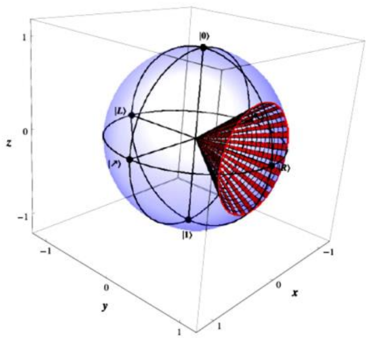
We prove the existence of a class of two–input, two–output gates any one of which is universal for quantum computation. This is done by explicitly constructing the three–bit gate introduced by Deutsch [Proc. R. Soc. London. A **425**, 73 (1989)] as a network consisting of replicas of a single two–bit gate.

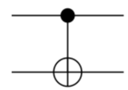
Распространённые универсальные наборы гейтов:

1) $\{R_x, R_y, R_z, Ph, \mathrm{CNOT}\}$



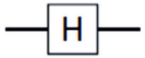
$$R_y = \begin{bmatrix} \cos(\theta/2) & -\sin(\theta/2) \\ \sin(\theta/2) & \cos(\theta/2) \end{bmatrix}$$

CNOT



$$P(\varphi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{bmatrix}, \qquad \varphi \in \mathbb{R}$$

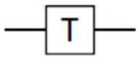
2) $\{H, S, T, \mathrm{CNOT}\}$



$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

Input	Output
$\|0\rangle$	$\frac{\|0\rangle + \|1\rangle}{\sqrt{2}}$
$\|1\rangle$	$\frac{\|0\rangle - \|1\rangle}{\sqrt{2}}$

$$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} = \sqrt{Z}$$

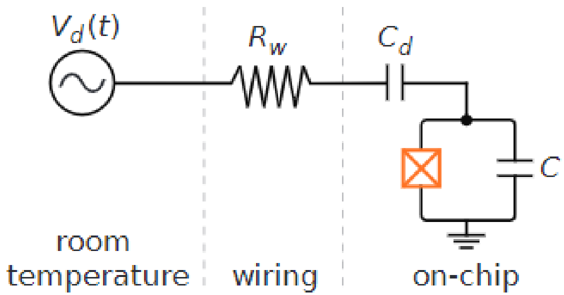


$$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix} = \sqrt[4]{Z}$$

3) $\mathrm{BARENCO}(\phi, \alpha, \theta)$

$$\mathrm{BARENCO} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & e^{i\alpha}\cos(\theta) & -ie^{i(\alpha-\phi)}\sin(\theta) \\ 0 & 0 & -ie^{i(\alpha+\phi)}\sin(\theta) & e^{i\alpha}\cos(\theta) \end{pmatrix}$$

Однокубитные гейты:

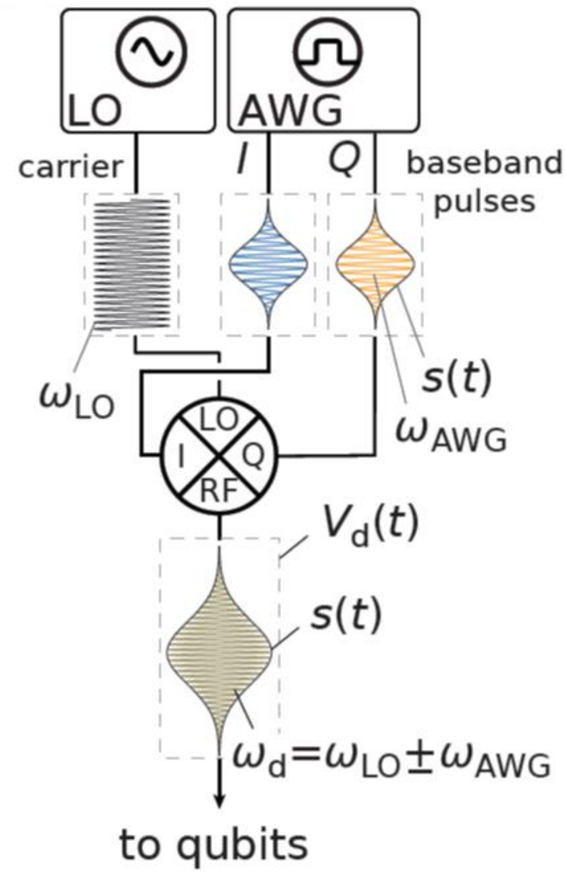


$$\widetilde{H}_{\mathrm{d}} = -\frac{\Omega}{2} V_0 s(t) \left(I\sigma_x + Q\sigma_y \right)$$

$I = \cos(\phi)$ (the 'in-phase' component)

$Q = \sin(\phi)$ (the 'out-of-phase' component)

$$U_{\mathrm{rf,d}}^{\phi=0}(t) = \exp\left(\left[\frac{i}{2} \Omega V_0 \int_0^t s(t') \mathrm{d}t' \right] \sigma_x \right)$$

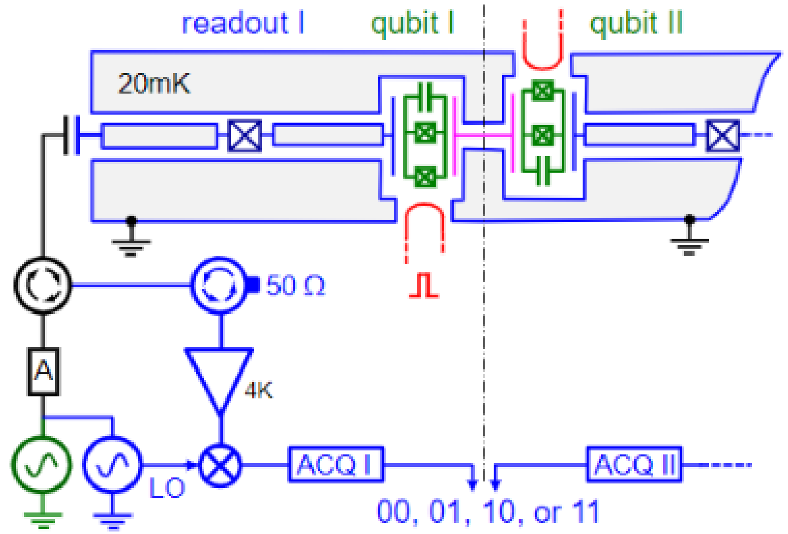


Двухкубитные гейты:

$$H_{qq} = -g\left([\sigma^+ - \sigma^-] \otimes [\sigma^+ - \sigma^-]\right)$$

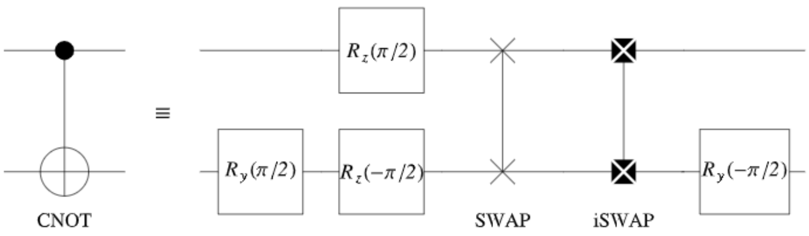
$$H_{qq} = g(e^{i\delta\omega_{12}t}\sigma^+\sigma^- + e^{-i\delta\omega_{12}t}\sigma^-\sigma^+)$$

$$H_{qq} = \frac{g}{2}(\sigma_x\sigma_x + \sigma_y\sigma_y)$$

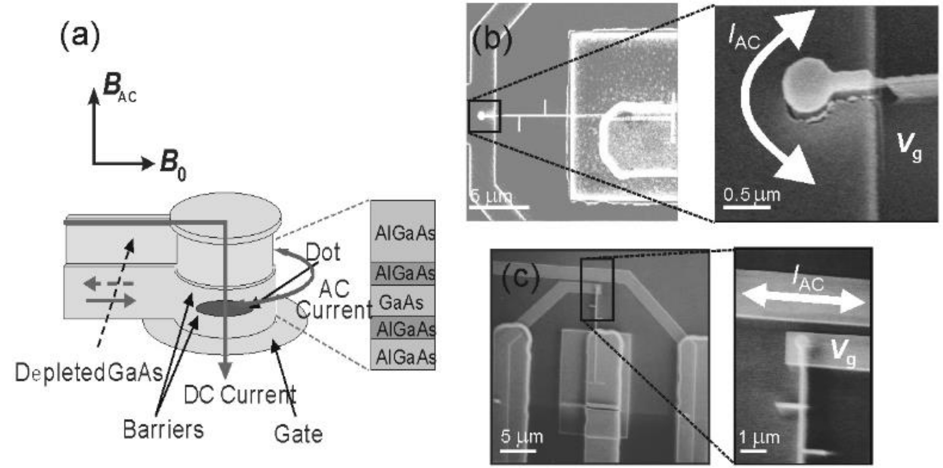


$$U_{qq}(t) = e^{-i\frac{g}{2}(\sigma_x\sigma_x+\sigma_y\sigma_y)t} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(gt) & -i\sin(gt) & 0 \\ 0 & -i\sin(gt) & \cos(gt) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

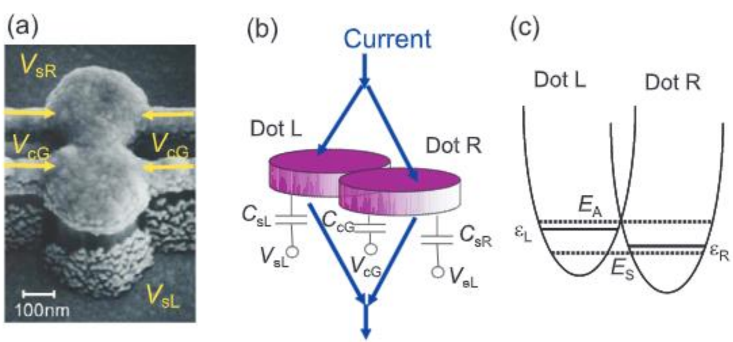
$$t = \frac{\pi}{2g} \qquad \text{iSWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$



Однокубитные гейты:



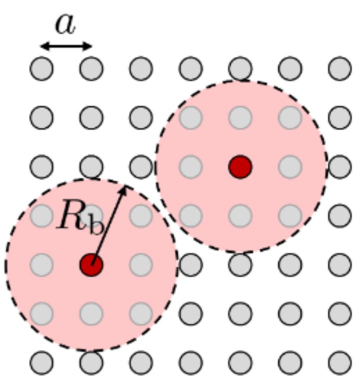
Двухкубитные гейты:

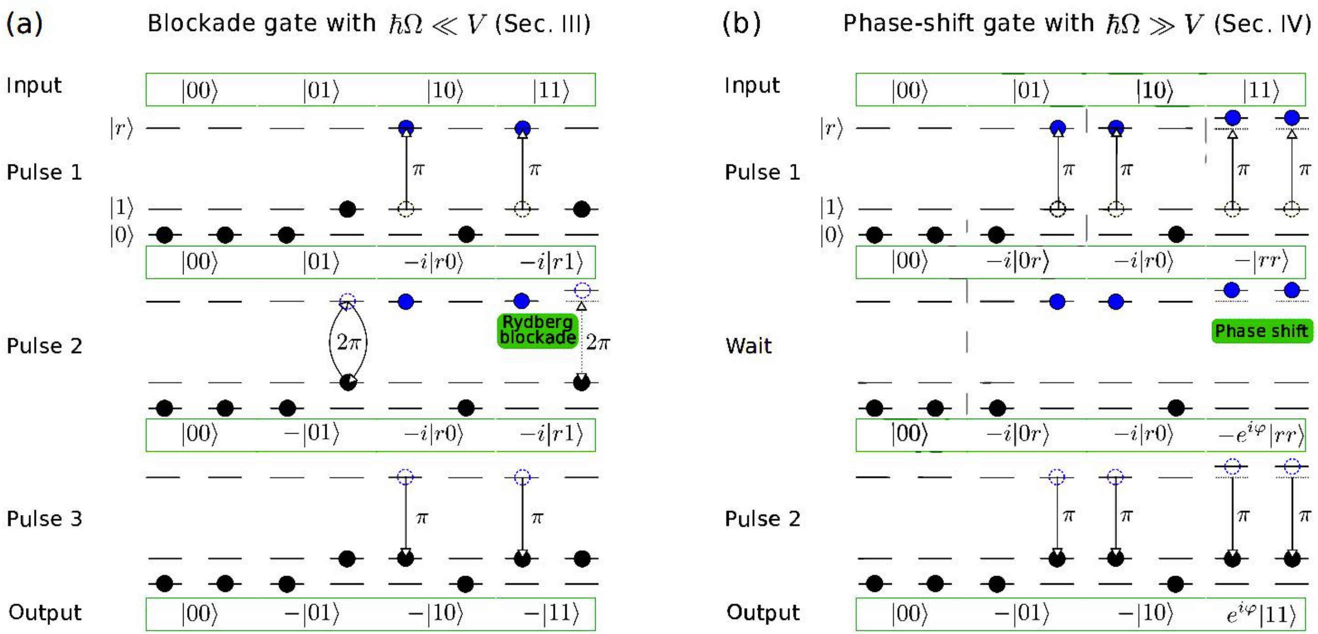


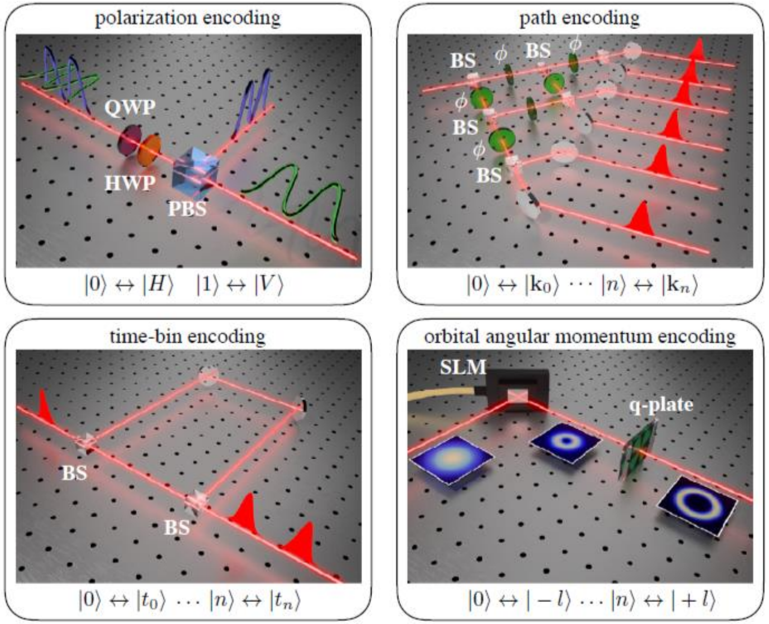
$$H_{\mathrm{int}}(t) = J(t)\mathbf{S}_1 \cdot \mathbf{S}_2.$$

$$\int \mathrm{d}t J(t)/\hbar = J\tau_{\mathrm{SWAP}}/\hbar = \pi \ (\mathrm{mod}\ 2\pi),$$

$$U(t) = \exp(\mathrm{i}) \int_0^t H_{\mathrm{int}}(\tau)\, \mathrm{d}\tau/\hbar, \quad \mathrm{SWAP}^{\alpha} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{1}{2}\left(1+e^{i\pi\alpha}\right) & \frac{1}{2}\left(1-e^{i\pi\alpha}\right) & 0 \\ 0 & \frac{1}{2}\left(1-e^{i\pi\alpha}\right) & \frac{1}{2}\left(1+e^{i\pi\alpha}\right) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

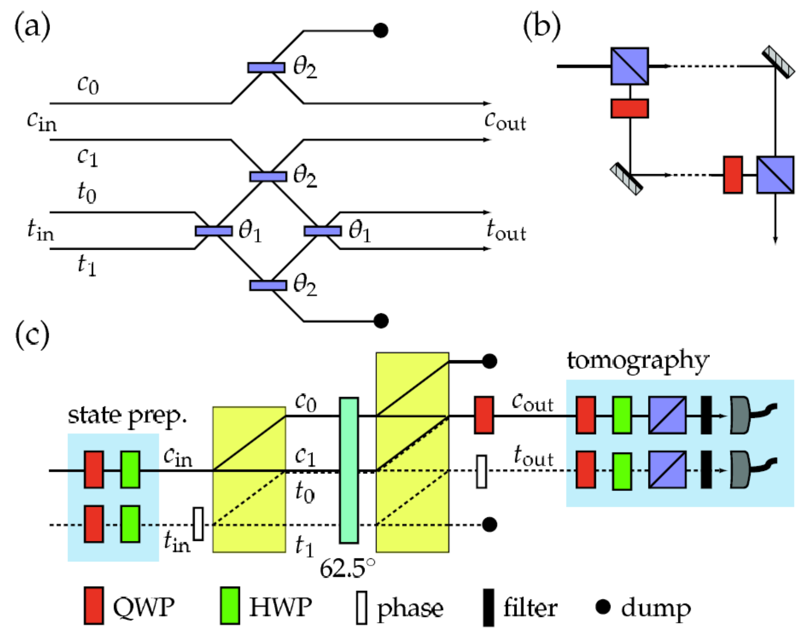

a
R_b


(a) Blockade gate with ħΩ ≪ V (Sec. III)
(b) Phase-shift gate with ħΩ ≫ V (Sec. IV)
Input
Pulse 1
Pulse 2
Pulse 3
Wait
Output
|00⟩ |01⟩ |10⟩ |11⟩
|r⟩ |1⟩ |0⟩
π
2π
−i|r0⟩ −i|r1⟩
−|01⟩
Rydberg blockade
−|10⟩ −|11⟩
−i|0r⟩ −|rr⟩
Phase shift
−e^{iφ}|rr⟩
e^{iφ}|11⟩

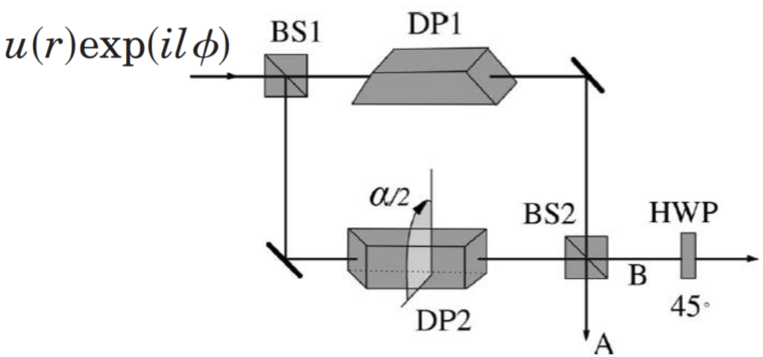


CNOT (Path encoding):

$$\theta_1 = \pi/4$$
$$\theta_2 = \arccos 1/\sqrt{3}$$



OAM-CNOT gate:



$$\alpha = \pi$$

$$\begin{pmatrix} A \\ B \end{pmatrix} = \frac{1}{2} u(r)\exp(il\phi) \begin{pmatrix} 1 + \exp(il\pi) \\ 1 - \exp(il\pi) \end{pmatrix}$$

Спасибо за внимание!